Initiation of arc magmatism in an embryonic continental rifting zone of the southernmost part of Okinawa Trough

Sun-Lin Chung[1]*, Shing-Lin Wang[1], Ryuichi Shinjo[2], Chao-Shing Lee[3] and Cheng-Hong Chen[1]

[1]*Department of Geosciences, National Taiwan University, 245 Choushan Road, Taipei 106, Taiwan;* [2]*Department of Physics and Earth Sciences, University of the Ryukyus, Okinawa, Japan;* [3]*Institute of Applied Geophysics, National Taiwan Ocean University, Keelung, Taiwan*

ABSTRACT

The Okinawa Trough is a young, intracontinental backarc basin that has formed behind the Ryukyu arc–trench system since late Miocene time. In the Southernmost Part of the Okinawa Trough (SPOT), a cluster of active submarine volcanoes delineates a volcanic belt, which is located only ~100 km above the Wadati–Benioff zone. We report herein new major and trace element data for the SPOT volcanic rocks. These rocks show a compositional range from medium-K andesite to rhyolite. Their geochemical characteristics are similar to those of pre-backarc rifting volcanic rocks from the central Ryukyu arc, and different from those of backarc basin lavas from the Middle Okinawa Trough and the post-backarc rifting Ryukyu arc volcanics. Therefore, despite being topographically contiguous with the rest of the Trough, the SPOT that developed in the Quaternary is not a simple backarc basin but instead an embryonic rift zone in which early arc volcanism occurs as a result of the Ryukyu subduction.

Terra Nova, 12, 225–230, 2000

Introduction

Backarc basins result from lithospheric extension that occurs behind or, in some cases, within magmatic arcs at the convergent margins. Thus, the formation age of backarc basins is generally younger than that of the associated arcs (cf. Taylor, 1995). The Okinawa Trough, extending from SW Kyushu to NE Taiwan (Fig. 1), is widely regarded as an intracontinental backarc basin that is built behind the Ryukyu arc–trench system owing to subduction of the Philippine Sea plate underneath the Eurasian plate (Lee *et al*., 1980; Letouzey and Kimura, 1986; Sibuet *et al*., 1987). In addition to the modern activity (< 0.1 Ma; Sibuet *et al*., 1995), two phases of crustal extension in the late Miocene (~10–6 Ma) and Pleistocene (~2–0.1 Ma) epochs, with ~4 Myr tectonic intermission, have been documented in the middle and northern parts of the Okinawa Trough (see Sibuet *et al*., 1998, for a review). In its southernmost part, the SPOT (i.e. SW of ~123°E; Fig. 1), however, structural (Hsu *et al*., 1996) and sedimentary (Park *et al*., 1998) events have been limited to the Quaternary. Thus, in contrast to an apparently simple backarc environment in the middle–northern part of the Trough, the SPOT may have formed through a different, more complicated, kinematic mode that was probably affiliated with the tectonic evolution of the arc–continent collision in Taiwan (Lee *et al*., 1998b). Wang *et al*. (1999) proposed that postcollisional extension in the northern Taiwan mountain belt, which commenced around Plio-Pleistocene time, caused the northern Taiwan volcanic zone activity (Fig. 1). Moreover, this extension played a role in reactivating the Pleistocene rifting in the Middle Okinawa Trough and gave room for its southwestward propagation with associated development of the Ryukyu subduction zone to Taiwan (Shinjo *et al*., 1999).

Sibuet *et al*. (1998) presented a detailed bathymetric map and seismic reflection profiles of the SPOT, according to which ~70 active submarine volcanoes, are located ~100 km above the Wadati–Benioff zone, can be identified (Lee *et al*., 1998a; unpubl. data). Based on topographic data, Sibuet *et al*. (1998) proposed that three types of magmatism exist there–represented by arc, backarc and 'cross-backarc'-type volcanoes–and ascribed the intense magma production to underthrusting of the Gagua Ridge in the western margin of the Philippine Sea plate (Fig. 1). In order to decode the petrochemical characteristics of different types of the SPOT magmas and thus understand the tectonic setting for such magmas, new geochemical data are reported from volcanic rocks dredged from the SPOT region by the *Ocean Research I* (Taiwan) and *T/S Nagasaki Maru* (Japan) cruises. These data indicate that all the SPOT lavas show calc-alkaline affinities and may be explained as products of early arc volcanism caused by the southwestward propagation of the Ryukyu subduction zone. Together with the fact that in the SPOT the rifting event took place broadly synchronously or prior to the volcanism, it is suggested that the SPOT is not a backarc basin as often thought.

Correspondence: Tel.: +886/2-83691242; Fax: +886/2-23636095; E-mail: sunlin@ccms.ntu.edu.tw

Samples and analytical results

Volcanic rocks were dredged from 11 submarine volcanoes in the SPOT central graben region (Fig. 1b), which include the three types of volcanic domains suggested by Sibuet *et al*. (1998). Among these, 20 fresh samples from five dredging sites were used for geochemical analysis and 3 of them (sample # DR2-1, DR4-2 and RN-D9P) subjected to Ar–Ar dating. Whereas the DR samples are too young (< 0.1 Myr age) to date reliably, the last one gives a plateau age of 0.15 ± 0.08 (2σ) Myr (Chung *et al*., unpubl. data). Major and trace element analyses were also carried out for 13 samples from Kueishantao, an emerged islet located at the western end of the SPOT volcanic field that consists dominantly of andesitic lava flows (Chen *et al*., 1995). The main volcanic activity on this islet occurred 7.0 ± 0.7 ka (Chen *et al*. 2000). Analytical methods used and representative results of these SPOT lavas are given in Table 1. For comparison, major and trace element data of a rhyolite (RN-D6P) dredged from the submerged volcanic front of southern Ryu-

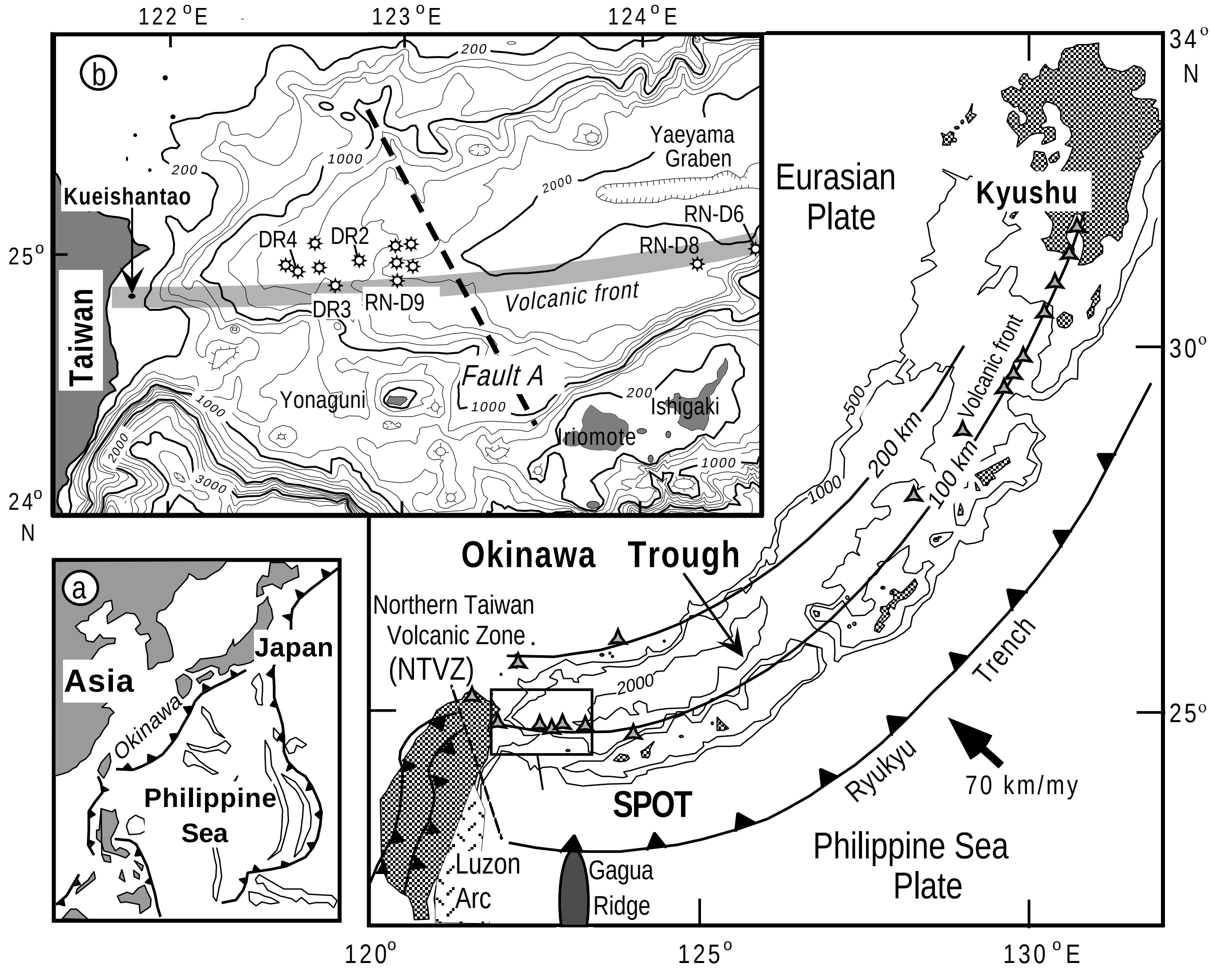

Fig. 1 Map showing the tectonic framework of the Ryukyu arc-backarc system. Asterisks indicate Quaternary volcanoes that comprise the present-day Ryukyu volcanic front and the northern Taiwan volcanic zone (NTVZ) in the north of southern Okinawa Trough. Bathymetric contours are in metres. Modified from Shinjo *et al.* (1999) and Wang *et al.* (1999). Inset (a), major tectonic units surrounding the Philippine Sea; inset (b), locations of Kueishantao islet and dredging sites for submarine volcanoes are indicated. A broad line marks the southern Ryukyu volcanic front (Sibuet *et al.*, 1998) and dashed line shows the trajectory of Fault A (Hsu *et al.*, 1996).

kyus (Shinjo *et al.*, 1998), in the east of the SPOT (Fig. 1b), are also listed.

These results indicate that the SPOT magmas possess a rather wide range of composition from andesite to rhyolite ($SiO_2 \approx$ 58–73 wt%). Although mafic rocks have not been recovered, this compositional range differs from that delineated by the remainder of the Okinawa Trough, where magmas show a bimodal composition (Shinjo *et al.*, 1999). The SPOT rocks plot in the higher portion of the median-K field in the SiO_2 vs. K_2O diagram (Fig. 2a), similar to early to middle Miocene ($\sim$21–13 Myr old) volcanic rocks from the central Ryukyu arc, which were emplaced before the Okinawa Trough opening (Shinjo *et al.*, 1999). The incompatible element variation patterns of the SPOT magmas are marked by relative enrichment in the large ion lithophile elements (LILE; Cs, Rb and Ba) and Th, U and Pb, and depletion in the high field-strength elements (HFSE; Nb, Ta and Ti) (Fig. 2b), a feature typical of arc magmas from the Ryukyu subduction zone (Shinjo *et al.*, 1999) as well as other convergent plate margins (Tatsumi and Eggins, 1995). The SPOT magmas, moreover, show remarkable geochemical variations from contemporaneous arc volcanics obtained from an adjacent region in southern Ryukyu. In the K_2O vs. SiO_2 plots (Fig. 2a), the southern Ryukyu arc lavas (those from RN-D6 and RN-D8; Fig. 1b), which are also of intermediate to acidic compositions, have lower potassium and thus straddle the median-K and low-K fields. These lavas reveal different chondrite-normalized rare earth element (REE) patterns (Fig. 3), with less enriched light REE (e.g. La and Ce) but apparently higher heavy REE concentrations, from the SPOT magmas. Hence, it can be inferred that, to a certain exten several scenarios of magma production took place between the SPOT and its eastern counterpart under a similar Ryukyu subduction context.

Comparison with the central Ryukyu arc–backarc system

Shinjo *et al.* (1999) documented a secular change in magma compositions in

Table 1 Major and trace element data of representative volcanic rocks from the SPOT area

Sample No.	KST-3	KST-10	DR2–1	DR3–2	DR4–2	DR4–3	RN-D9P†	RN-D6P†
Major elements (wt.%)*								
SiO_2	58.34	61.43	72.91	72.25	60.63	64.96	65.16	74.82
TiO_2	0.71	0.53	0.30	0.30	0.57	0.60	0.40	0.19
Al_2O_3	17.01	14.29	13.84	13.67	15.72	15.29	19.53	13.08
Fe_2O_3	7.70	6.60	2.62	2.60	6.96	5.64	4.12	3.13
MnO	0.12	0.11	0.05	0.07	0.12	0.09	0.08	0.12
MgO	3.78	5.01	0.54	0.47	3.60	2.05	1.23	0.21
CaO	6.66	6.04	2.26	2.17	6.86	4.93	3.88	2.34
Na_2O	2.69	2.28	3.64	3.74	2.44	2.88	2.84	4.90
K_2O	1.78	2.18	2.86	3.04	1.65	2.18	2.42	1.08
P_2O_5	0.14	0.09	0.06	0.06	0.10	0.11	0.09	0.03
LOI	0.75	0.10	0.80	0.85	1.22	1.05	1.27	2.54
Total	99.68	98.64	99.90	99.22	99.86	99.77	99.75	99.90
Trace elements (ppm)*								
Sc	27	24	8.8	5.3	19	13	15	15
V	213	149	27	21	161	103	94	2
Cr	32	211	8	6	48	15	18	7
Co	24	22	3	3	18	10	8	1
Ni	12	37	4	6	9	6	5	1
Rb	59.5	72.9	130	93.3	51.6	68.2	106	31.8
Sr	305	200	90	83	132	126	180	113
Y	28.1	23.3	30.6	19.4	13.9	16.5	20.2	43.2
Zr	141	129	111	130	105	135	85	154
Nb	10.2	9.53	8.69	7.37	5.46	7.30	6.90	3.70
Cs	1.71	3.65	5.73	5.44	3.14	4.18	5.73	1.71
Ba	388	377	515	502	275	364	387	225
La	21.5	21.6	28.0	28.1	15.3	20.8	22.4	11.6
Ce	45.2	45.8	56.3	56.5	33.4	43.9	43.9	26.6
Pr	5.42	5.30	6.77	6.09	3.85	7.98	4.63	3.43
Nd	21.7	20.4	24.0	20.7	13.9	17.9	17.1	15.7
Sm	4.70	4.34	4.83	4.46	3.07	3.88	3.39	4.42
Eu	1.02	0.83	0.73	0.49	0.50	0.56	0.75	1.15
Gd 4.43	3.93	4.51	3.11	2.25	2.75	3.29	5.28	
Tb	0.75	0.66	0.81	0.53	0.37	0.45	0.52	0.98
Dy	4.54	4.00	5.08	3.12	2.26	2.62	3.05	6.25
Ho	0.97	0.84	0.97	0.64	0.45	0.54	0.64	1.39
Er	2.77	2.39	2.87	1.88	1.35	1.59	1.90	4.23
Tm	0.41	0.35	0.45	0.29	0.20	0.25	0.30	0.69
Yb	2.63	2.30	2.99	1.89	1.28	1.55	1.97	4.51
Lu	0.39	0.34	0.47	0.30	0.20	0.24	0.31	0.71
Hf	3.68	3.40	3.80	4.25	2.93	3.81	2.25	3.63
Ta	0.78	0.79	0.76	0.72	0.46	0.60	0.56	0.26
Pb	6.24	8.63	13.9	13.1	9.14	11.5	15.5	5.62
Th	7.82	8.06	8.84	12.5	6.47	9.25	9.22	3.25
U	1.69	1.75	1.84	2.70	1.39	1.86	1.82	0.81

*Major elements were determined by X-ray fluorescene spectrometry at National Taiwan University and trace elements were determined by inductively induced plasma-mass spectromotry at Guangzhou Institute of Geochemistry. Analytical details were reported by Wang *et al.* (1999).

†Data from Shinjo *et al.* (1998) for major elements and Shinjo *et al.* (unpubl. data) for trace elements.

the central Ryukyu arc–Middle Okinawa Trough (backarc) system that may offer clues to understanding the geochemical variation between the SPOT and remaining southern Ryukyu volcanic rocks. In central Ryukyu, arc volcanism occurred in two phases, in the early middle Miocene (~21–13 Ma) and the latest Miocene (~6–4 Ma), respectively, i.e. before and after the first stage (~10–6 Ma) of the Okinawa Trough opening. Arc volcanism ceased when rifting in the backarc basin was active. With a shared compositional range from basalt to rhyolite, the two volcanic phases define two distinct trends in the K_2O vs. SiO_2 plots (Fig. 2a). The post-backarc-opening arc lavas are less enriched in the incompatible elements (LILE and LREE) and possess higher concentrations of Y and HREE than the prebackarc opening lavas. This is illustrated in the REE diagram (Fig. 3a), in which arc volcanics of the early phase display 'steeper' REE patterns [$(La/Yb)_N \approx 5.8$–3.7] than those of the later phase [$(La/Yb)_N \approx 3.3$–1.5] (Shinjo *et al.*, 1999). Contribution by shallow-level processes, e.g. crystal fractionation and crustal contamination, has been considered insignificant for such a secular variation because only mafic rocks with rather primitive compositions were used for comparison (Wang, 1998; Shinjo *et al.*, 1999). Given that Sr–Nd isotope compositions of the two volcanic phases are similar (Shinjo *et al.*, 1999), the secular variation may be interpreted as a result of a change of thermal structure in the mantle wedge resulting from opening of the Okinawa Trough that could have caused attenuation of the lithosphere and upwelling of the asthenosphere. Therefore, the later phases of the central Ryukyu arc lavas were generated by increasing degrees of melting and shallower depths of magma segregation (Shinjo *et al.*, 1999).

Although magmatism synchronous with the first stage of Okinawa Trough opening is yet to be established, the second stage of opening was associated with intense volcanic activity commencing ~1.5 Ma (Wang, 1998) in the axial zone of the Middle Okinawa Trough (Shinjo *et al.*, 1999). These Quaternary magmas show bimodal compositions dominated by basalt and rhyolite. As reported by Shinjo *et al.* (1999), whereas most of these basalts are low-K tholeiites (Fig. 2a), which have major element systematics comparable to those from mature backarc basins, these magmas show arc-like trace element signatures (e.g. relatively enriched in LILE and Pb and depleted in HFSE). These signatures are explained by the Trough being an incipient backarc basin with a prolonged early rifting stage (Sibuet *et al.*, 1998). Two mantle source components, an upwelling asthenosphere and a 'subduction component', have been proposed for the magma generation (Shinjo *et al.*, 1999). The associated rhyolites are sodium-rich ($Na_2O/K_2O \approx 2.8$–1.5) and possess Nd isotope ratios (εNd ≈ +5.1 to +2.5) similar to those of the basalts. This suggests a cognate magma origin, i.e. both the basalts and rhyolites are

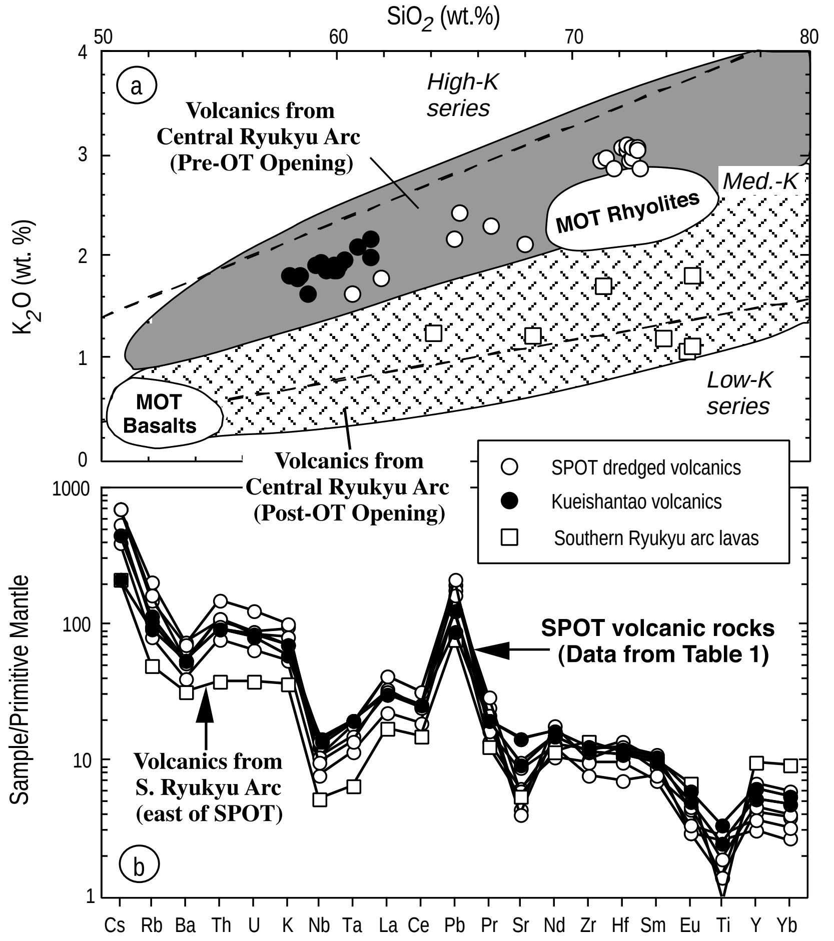

Fig. 2 (a) K_2O vs. SiO_2 plots and (b) primitive mantle-normalized elemental variation patterns of the SPOT volcanic rocks. In (a), data of dredged volcanic rocks from the southern Ryukyu arc, east of the SPOT (Shinjo *et al.*, 1998; unpubl. data), are also plotted. Fields for magmas from the central Ryukyu arc (pre-and post-Okinawa Trough opening) and the middle Okinawa Trough (MOT) are based on Shinjo *et al.* (1999; references therein). Normalizing values for the N-type mid-ocean ridge basalt (MORB) are from Sun and McDonough (1989).

essentially mantle-derived, and crustal contamination, if any, played only a minor role during magma ascent and differentiation (Wang, 1998; Shinjo and Kato, 2000). In comparison to the Ryukyu arc lavas, these backarc basin magmas are marked by composition bimodality and significantly higher Nd and lower Sr isotope ratios. The backarc basin basalts are less enriched in LILE and LREE than the post-backarc opening lavas from central Ryukyu (Shinjo *et al.*, 1999). Consequently, decompression melting of the ascending asthenosphere caused by substantial lithospheric thinning is a likely process governing the magma generation in the middle part of Okinawa Trough.

Mechanism for initiating the SPOT volcanism

The present data indicate that no matter where the SPOT lavas were recovered [from the arc (DR-3 and RN-D9), backarc (DR-4) or abnormal 'cross-backarc' (DR-2) types of volcanoes proposed by Sibuet *et al.* (1998)], they demonstrate coherent geochemical characteristics that are comparable to the pre-backarc rifting arc volcanics from central Ryukyu. Coexistence of arc and backarc volcanism in a small area like the SPOT is most unlikely. Whereas magma generation in the backarc basin requires upward convection of the asthenosphere, which would trigger decompression melting, in the arc setting it is essentially controlled by dehydration from the subduction zone, so that the solidus of the mantle wedge is depressed to cause melting. Thus, the central Ryukyu arc and backarc lavas display different isotope compositions because of the different magma source components involved (Shinjo *et al.*, 1999; 2000). According to Chen *et al.* (1995; unpubl. data), the SPOT magmas possess Sr ($^{87}Sr/^{86}Sr > 0.705$) and Nd ($\varepsilon Nd \approx -2$ to -5) isotope ratios, which can be discriminated from those of backarc magmas from the Middle Okinawa Trough (with εNd values up to + 5) and correspond to those of certain arc volcanics from central and northern Ryukyus (Shinjo *et al.* 2000). Hence, it is proposed that Ryukyu subduction, rather than intracontinental (backarc) rifting, serves as the governing process for the SPOT magmatism.

This argument is consistent with the tectonic configuration of volcanoes in the SPOT comprising a volcanic belt ~100 km above the Wadati–Benioff zone (Fig. 1), the location where the volcanic fronts are observed in the northern Ryukyu subduction zone (Fig. 1) and other convergent margins (Tatsumi and Eggins, 1995). Recent studies (Hsu *et al.*, 1996; Ujiié *et al.*, 1997; Park *et al.*, 1998; Sibuet *et al.*, 1998) have repeatedly shown that the SPOT is an embryonic geological feature and its development was restricted to the Quaternary epoch. The continental crust hence remains intact (~30-km thick) beneath the SPOT area, in contrast to an apparently thinner crust (~15 km) in the Middle Okinawa Trough (Sibuet *et al.*, 1987). It is thus reasonable to regard the SPOT as an incipient extension zone created by the southwestward propagation of the Okinawa Trough rifting that has little effect on the magma generation. Such a mode of rift propagation, relating to the Plio–Pleistocene extensional collapse of the northern Taiwan mountain belt (Wang *et al.*, 1999), was accompanied by southwestward migration of the Ryukyu subduction system, which resulted in the SPOT volcanism. In this sense, volcanoes within the SPOT are products of early arc magmatism. Despite its topographic continuation with the rest part of the Trough, the SPOT is unlikely, by definition, to be a simple backarc basin because it developed broadly synchronously or even prior to the early arc volcanism.

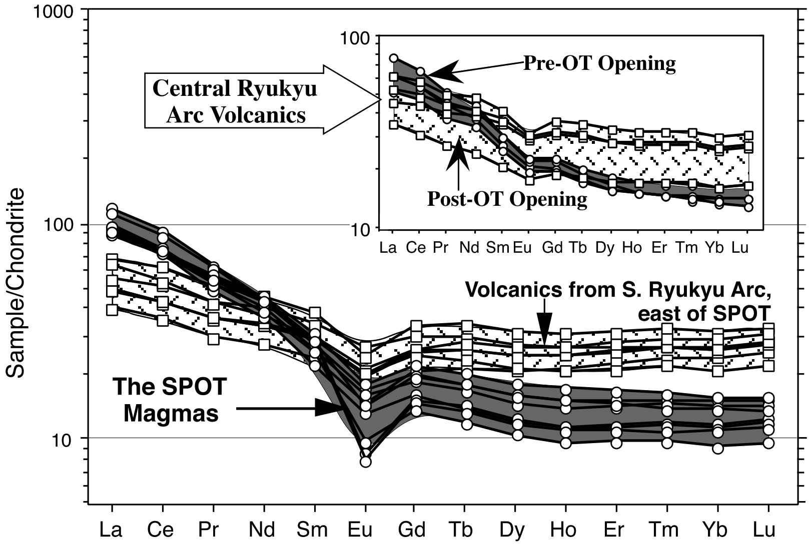

Fig. 3 Chondrite-normalized REE patterns of volcanic rocks dredged from the SPOT and its eastern region. Inset, REE patterns of the two stages of Miocene arc volcanics from central Ryukyus for comparison. Chondrite normalizing values are from Sun and McDonough (1989).

The spatial variation of magma compositions between the SPOT and its eastern region implies a difference between the lithospheric and/or thermal structure underneath the SPOT and that of its eastern counterpart. Remarkably, lavas from the eastern part of the southern Ryukyu volcanic front (RN-D6 and RN-D8) exhibit SiO_2–K_2O correlations (Fig. 2b) and REE patterns (Fig. 3) comparable with the latest Miocene, post-backarc opening arc volcanics from central Ryukyu. Thus, in this part of southern Ryukyu, arc lavas could have formed in a setting akin to central Ryukyu, i.e. with a well-developed rift zone in the backarc side under which the continental lithosphere has been stretched rather substantially. Such an interpretation is inconsistent with the observation, east of the SPOT area, that the southern Ryukyu arc–backarc system has existed since middle Miocene times (Shinjo *et al.*, 1999). It is speculated herein that the 'boundary' of variation in the magma composition, or inferred change of the lithospheric structure, exists $\sim$123–124°E in the Trough (Fig. 1b), corresponding to the strike-slip Fault A documented by Hsu *et al.* (1996). From here, the second phase of the Okinawa Trough rifting may have propagated rapidly southwestward (at a rate of $\sim$126 mm yr^{-1}; Liu, 1995) with a clockwise rotation of $\sim$15° (Miki, 1995), to form the SPOT and the complex collision/extension/subduction tectonic context off Taiwan (Lee *et al.*, 1998b; Wang *et al.*, 1999).

Concluding remarks

Geochemical data reported herein suggest that early arc volcanism occurs in the SPOT, an embryonic continental extension zone formed by rift propagation from the Okinawa Trough in the north-east. This is analogous to the case observed in the southern Harve Trough where the active Kermadec volcanic front lies in the axial rift grabens and interaction of migrating arc volcanism with backarc extension have been documented by Wright *et al.* (1996). The present results provide important clues to understanding not only the regional tectono-magmatic evolution, but also the geochemical characteristics of early arc magmatism in the intracontinental convergent margins, which, marked by the median-K calc-alkaline nature, differ from those observed in the intraoceanic setting, where early arc lavas display more depleted boninitic or tholeiitic compositions (Bloomer *et al.*, 1995). In the SPOT, intense submarine volcanoes associated with active hydrothermal venting, a deep-water biological community (Lee *et al.*, 1998a; unpubl. data) and shallow ($\sim$10–40 km) earthquakes (Sibuet *et al.*, 1998), deserve further detailed investigations to study how early arc magmatism occurs and continental rift begins.

Acknowledgements

We thank Y.G. Chen, S.K. Hsu, T.Y. Lee, C.S. Liu, C.H. Lo and K.L. Wang for useful discussion and/or sharing unpublished information, and J.-C. Sibuet and Y. Tatsumi for their insightful reviews, which significantly improved the paper. This study benefited from financial supports by the National Science Council, Taiwan, ROC and the Ministry of Education, Science, Sports and Culture, Japan.

References

Bloomer, S.H., Taylor, B., MacLeod, C.J. *et al.*, 1995. Early arc volcanism and the ophiolite problem: A perspective from drilling in the western Pacific. In: *Active Margins and Marginal Basins of the Western Pacific* (B. Taylor and J. Natland, eds). *Geophys. Monogr. Am. geophys. Un.*, **88**, 1–30.
Chen, C.H., Lee, T., Hsieh, Y.N., Chen, C.-H. and Hsu, W.Y., 1995. Magmatism at the onset of back arc basin spreading in Okinawa Trough. *J. Volcanol. Geotherm. Res.*, **69**, 313–322.
Chen, Y.G., Wu, W.S., Liu, T.K. and Chen, C.-H., 2001. A date for volcanic eruption inferred from a siltstone xenolith. *Quat. Sci. Rev.*, **20**, 869–873.
Hsu, S.K., Sibuet, J.-C., Monti, S., Shyu, C.T. and Liu, C.S., 1996. Transition between the Okinawa Trough backarc extension and the Taiwan collision: New insights on the southernmost Ryukyu subduction zone. *Mar. Geophys. Res.*, **18**, 163–187.
Lee, C.S., Shor, G. Jr, Bibee, L.D., Lu, R.S. and Hilde, T.W.C., 1980. Okinawa Trough: Origin of a back-arc basin. *Mar. Geol.*, **35**, 219–241.
Lee, C.S., Tsai, C.F., Chung, S.L. and the SPOT members, 1998a. Active interaction of submarine volcanoes and ocean current in the southernmost part of Okinawa Trough. *EOS, Trans. Am. Geophys. Un.*, **79**, F858.
Lee, T.Y., Chiang, C.S., Kong, F., Chung, S.L. and Lo, C.H., 1998b. Kinematics of the opening the southernmost part of Okinwa Trough. *EOS, Trans. Am. Geophys. Un.*, **79**, W120.
Letouzey, J. and Kimura, M., 1986. The Okinwa Trough genesis, structure and evolution of a backarc basin developed in a continent. *Mar. Petrol. Geol.*, **2**, 111–130.
Liu, C.C., 1995. The Ilan Plain and the southwestward extending Okinawa Trough. *J. Geol. Soc. China*, **38**, 329–342.

Miki, M., 1995. Two-phase opening model for the Okinawa Trough inferred from paleomagnetic study of the Ryukyu arc. *J. Geophys. Res.*, **100**, 8169–8184.

Park, J.-O., Tokuyama, H., Shinohara, M., Suyehiro, K. and Taira, A., 1998. Seismic record of tectonic evolution and backarc rifting in the southern Ryukyu island arc system. *Tectonophysics*, **294**, 21–42.

Shinjo, R. and Kato, Y., 2000. Geochemical constraints on the origin of bimodal magmatism at the Okinawa Trough, an incipient back-arc basin. *Lithos*, **54**, 117–137.

Shinjo, R., Motoyama, I., Nakamura, M. *et al.*, 1998. Report on RN97 cruise by *T/S Nagasaki Maru* in the Southern Okinawa Trough. *Bull. Coll. Sci. Univ. Ryukyu*, **65**, 39–51.

Shinjo, R., Chung, S.L., Kato, Y. and Kimura, M., 1999. Geochemical and Sr-Nd isotopic characteristics of volcanic rocks from the Okinawa Trough and Ryukyu Arc: Implications for the evolution of a young, intracontinental back arc basin. *J. Geophys. Res.*, **104**, 10591–10608.

Shinjo, R., Woodhead, J.D. and Hergt, J.M., 2000. Geochemical variation within the northern Ryukyu arc: Magma source compositions and geodynamic implications. *Contr. Miner. Petrol.*, **140**, 263–282.

Sibuet, J.-C., Letouzey, J., Barrier, F. *et al.*, 1987. Back arc extension in the Okinawa Trough. *J. Geophys. Res.*, **92**, 14,041–14,063.

Sibuet, J.-C., Hsu, S.K., Shyu, C.T. and Liu, C.S., 1995. Structural and kinematic evolutions of the Okinawa Trough backarc basin. In: *Backarc Basins: Tectonics and Magmatism* (B. Taylor, ed.), pp. 343–379. Plenum, New York.

Sibuet, J.-C., Deffontaines, B., Hsu, S.K. *et al.*, 1998. Okinawa Trough backarc basin: Early tectonic and magmatic evolution. *J. Geophys. Res.*, **103**, 30,245–30,267.

Sun, S.-S. and McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. In: *Magmatism in the Ocean Basins* (A.D. Saunders and M.J. Norry, eds). *Spec. Publ. Geol. Soc. London*, **42**, 313–345.

Tatsumi, Y. and Eggins, S., 1995. *Subduction Zone Magmatism*. Blackwell Science, Oxford, 211 pp.

Taylor, B. (ed.), 1995. *Backarc Basins: Tectonics and Magmatism*. Plenum, New York.

Ujiié, H., Nakamura, T., Miyamoto, Y., Park, J.-O. and Oyakawa, T., 1997. Holocene turbidite cores from the southern Ryukyu Trench slope: Suggestions of periodic earthquakes, *J. Geol. Soc. Japan*, **103**, 590–603.

Wang, K.L., Chung, S.L., Chen, C.H. *et al.*, 1999. Post-collisional magmatism around northern Taiwan and its relation with opening of the Okinawa Trough. *Tectonophysics*, **308**, 363–376.

Wang, S.L., 1998. *Ar-Ar dating and geochemistry of volcanic rocks from the middle Okinawa Trough. Unpubl.* Masters Thesis, National Taiwan University, Taipei, 141 pp.

Wright, I.C., Parson, L.M. and Gamble, J.A., 1996. Evolution and interaction of migrating cross-arc volcanism and backarc rifting: an example from the southern Harve Trough (35°20′–37°S). *J. Geophys. Res.*, **101**, 22,071–22,086.

Received 28 April 2000; revised version accepted 16 January 2001

